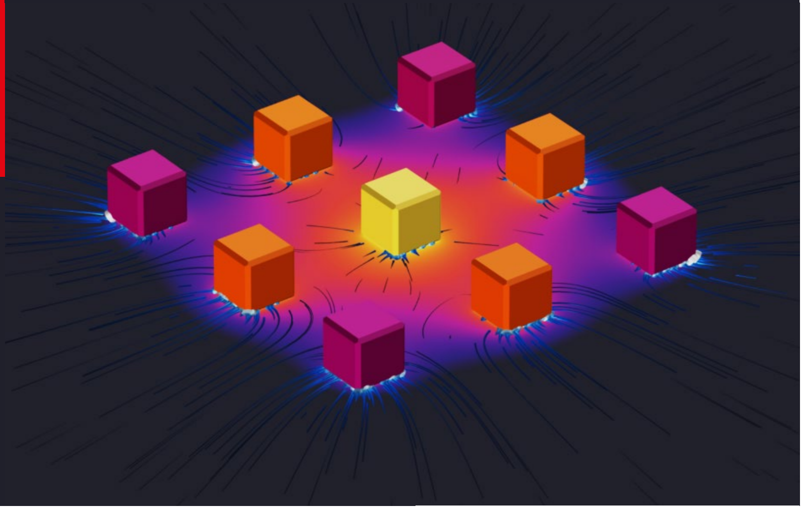
Heat and Mass Transfer
ME-341

Instructor: Giulia Tagliabue



École
polytechnique
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de Lausanne

Spring Semester

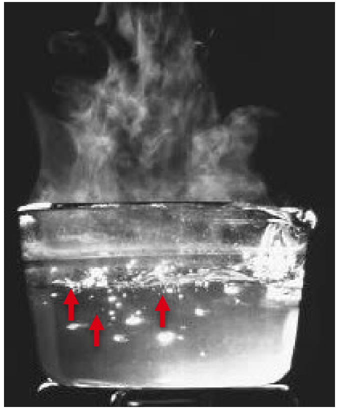
Previously

- ☑ Introduction to Boiling and Condensation
- ☑ Boiling Modes and Boiling Curves
- ☑ Pool Boiling Correlations

Learning Objectives:

- ☑ Understand the fundamentals of boiling
- ☑ Calculate heat transfer in pool boiling

Introduction to Boiling and Condensation



Boiling: heat transfer from the wall to the fluid

Condensation: heat transfer from the fluid to the wall

Fluid motion controlled by:

- Surface tension σ at the liquid-vapor interface
- Density difference (buoyancy) between liquid/vapor phases

Phase Transition = Isothermal Process

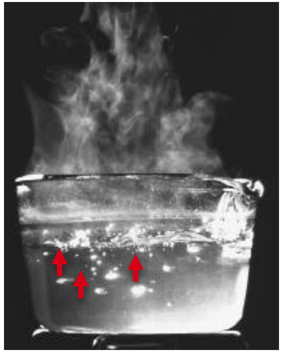
Latent heat (h_{fg}) is exchanged between solid and fluid

Small solid/fluid ΔT

Introduction to Boiling

Boiling occurs when the surface temperature exceeds the saturation temperature at that pressure.

$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e \qquad \Delta T_e \text{ excess temperature}$$



Fluid Dynamics

Pool boiling
the liquid is initially quiescent and only free convection occurs

Forced boiling
the fluid is moving while it boils (e.g. inside a pipe)

Heat Transfer

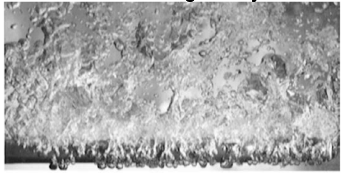
Saturated Boiling
$T_s > T_{sat}$, the bubble must rise

Subcooled Boiling
$T_s < T_{sat}$, the bubbles can re-condense in the liquid

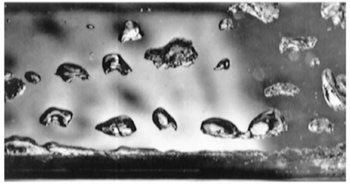
Saturated Pool Boiling

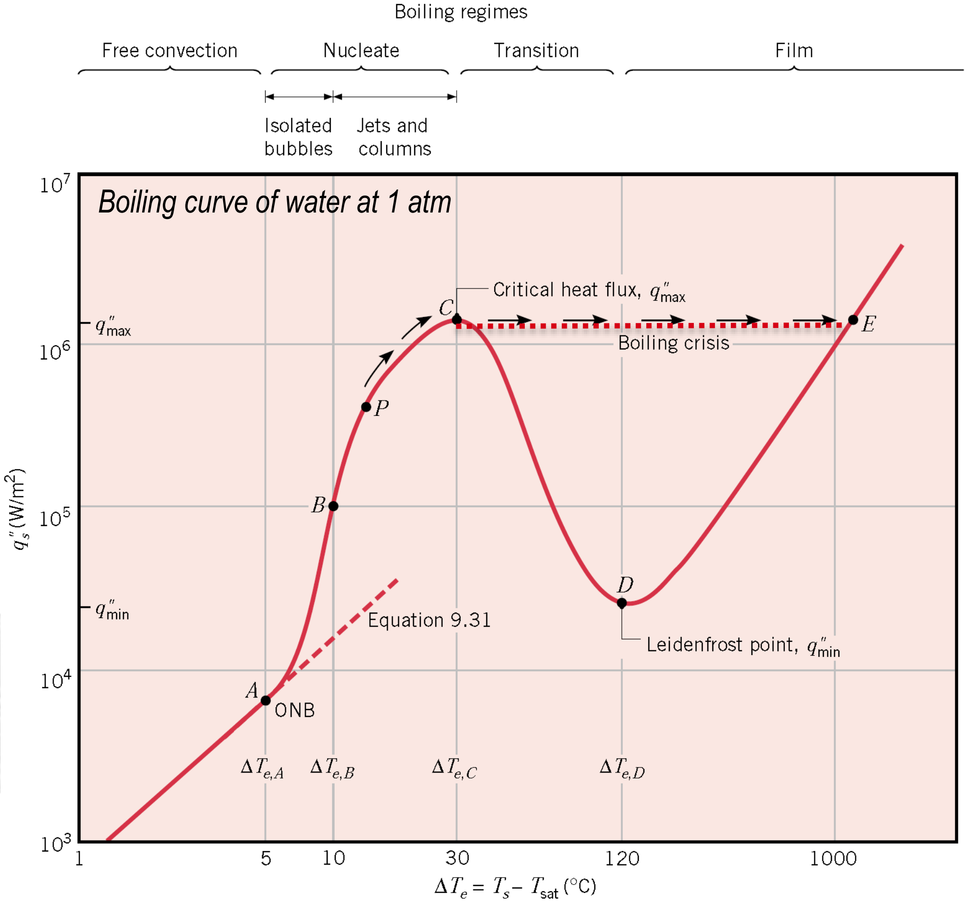
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

Nucleate boiling with jets



Film boiling



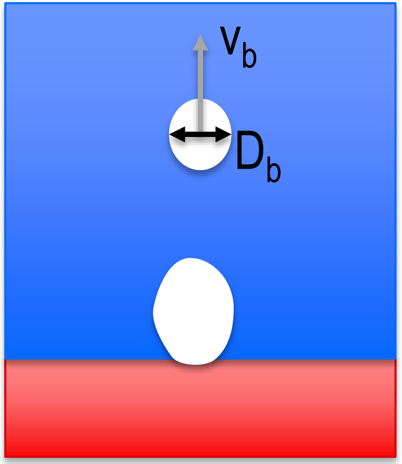


The solid curve is followed when we control ΔT_e. However in most applications we control q_s''. In such a case (as in the previous experiment) we observe:

C->E : boiling crisis - past the critical heat flux a film of vapor rapidly replaces isolated bubbles. The thermal conductivity of the vapor film is much less than that of the liquid and the surface temperature suddenly increases to much higher values

This can cause the failure of the component. Hence, when designing a heat exchanger we must be sure not to surpass the critical heat flux condition.

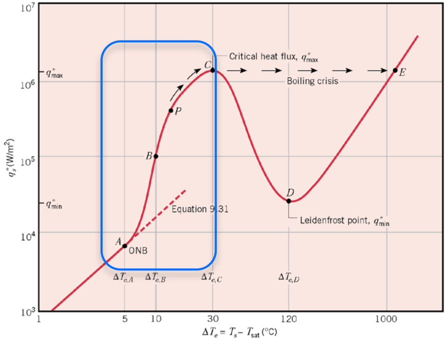
Nucleate Pool Boiling Correlations



$$q''_s = \mu_l h_{fg}\left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,l}\Delta T_e}{C_{s,f} h_{fg} Pr_l^n}\right)^3$$

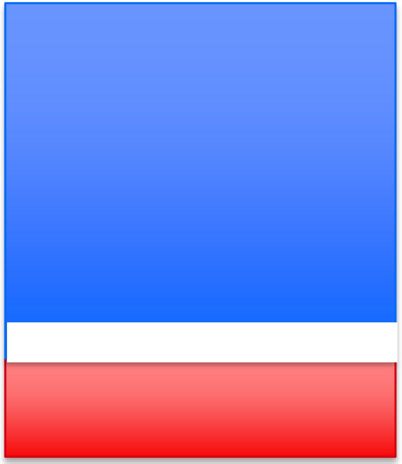
TABLE 10.1 Values of $C_{s,f}$ for various surface–fluid combinations [5–7]

Surface–Fluid Combination	$C_{s,f}$	n
Water–copper		
Scored	0.0068	1.0
Polished	0.0128	1.0
Water–stainless steel		
Chemically etched	0.0133	1.0
Mechanically polished	0.0132	1.0
Ground and polished	0.0080	1.0
Water–brass	0.0060	1.0
Water–nickel	0.006	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene–chromium	0.0101	1.7
Ethyl alcohol–chromium	0.0027	1.7



$$q''_{max} = C h_{fg}\rho_v\left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4}$$

Film Pool Boiling



$$\overline{Nu_D} = C\left[\frac{g\rho_v(\rho_l - \rho_v)h'_{fg}D^3}{\mu_v k_v(T_s - T_{sat})}\right]^{1/4}$$

Where $h'_{fg} = h_{fg} + 0.8c_{p.v}(T_s - T_{sat})$

$C = 0.62$ *for horizontal cylinders*

$C = 0.67$ *for spheres*

With properties estimated at $T_f = \frac{(T_s + T_{sat})}{2}$

If $T_s > 300C$, radiation is also present. We estimate the total convection coefficient as:

$$\bar{h} = \overline{h_{conv}} + \frac{3}{4}\overline{h_{rad}}$$

where $\overline{h_{conv}}$ has to be estimated with the previous correlation and $\overline{h_{rad}} = [\varepsilon\sigma(T_s^4 - T_{sat}^4)]/(T_s - T_{sat})$

This Lecture

- ❑ Forced Convection Boiling
  - ✓ External
  - ❑ Internal

Learning Objectives:

- ❑ Calculate heat flux and convection coefficient in forced convection boiling

Introduction to Boiling

Boiling occurs when the surface temperature exceeds the saturation temperature at that pressure.

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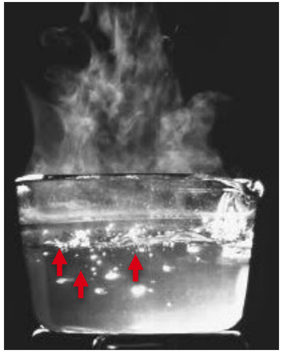

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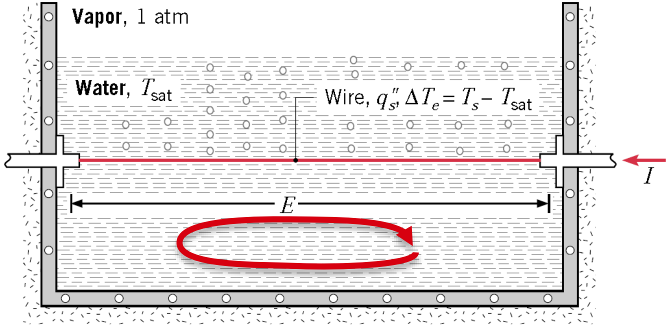
Forced Convection Boiling

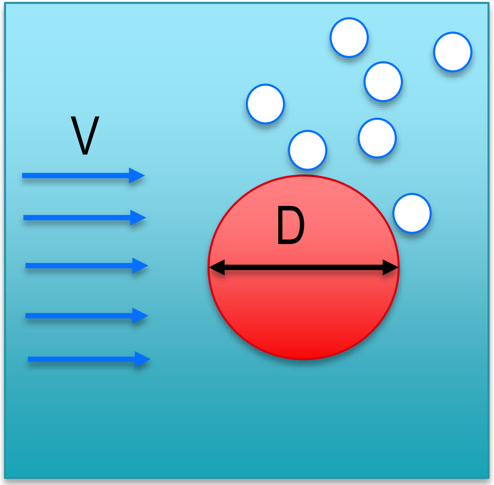


Buoyancy + Forced Convection

- External Flow
- Internal Flow (two-phase flow)

Forced Convection Boiling: External Flow (heat flux)

Cylinder



Use both correlations to calculate q''_{max}, then verify the validity conditions and keep the one that is true.

Low Velocity, i.e. $\frac{q''_{max}}{\rho_v h_{fg} V} > \left[\frac{0.275}{\pi}\left(\frac{\rho_l}{\rho_v}\right)^{1/2} + 1\right]$ **:**

$$\frac{q''_{max}}{\rho_v h_{fg} V} = \frac{1}{\pi}\left[1 + \left(\frac{4}{We_D}\right)^{1/3}\right]$$

High Velocity, i.e. $\frac{q''_{max}}{\rho_v h_{fg} V} < \left[\frac{0.275}{\pi}\left(\frac{\rho_l}{\rho_v}\right)^{1/2} + 1\right]$ **:**

$$\frac{q''_{max}}{\rho_v h_{fg} V} = \frac{\left(\frac{\rho_l}{\rho_v}\right)^{3/4}}{169\pi} + \frac{\left(\frac{\rho_l}{\rho_v}\right)^{1/2}}{19.2\pi {We_D}^{1/3}}$$

Where $We_D = \frac{\rho_v V^2 D}{\sigma}$

V **= fluid velocity**

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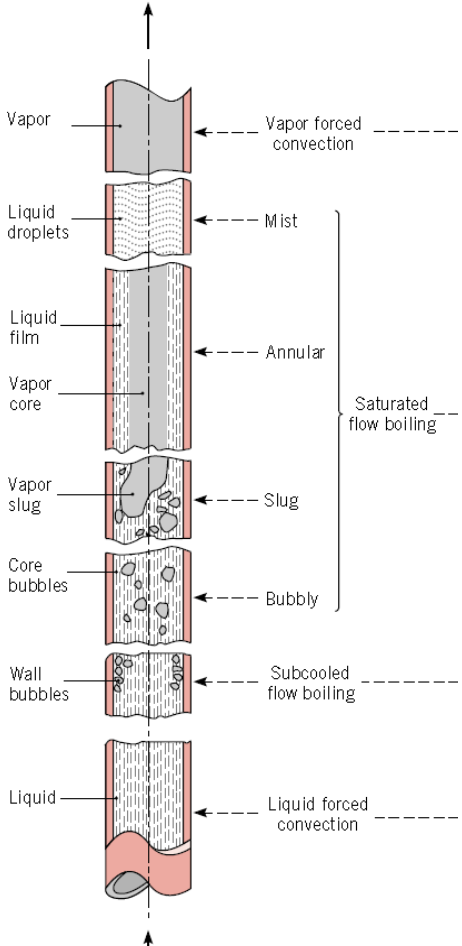
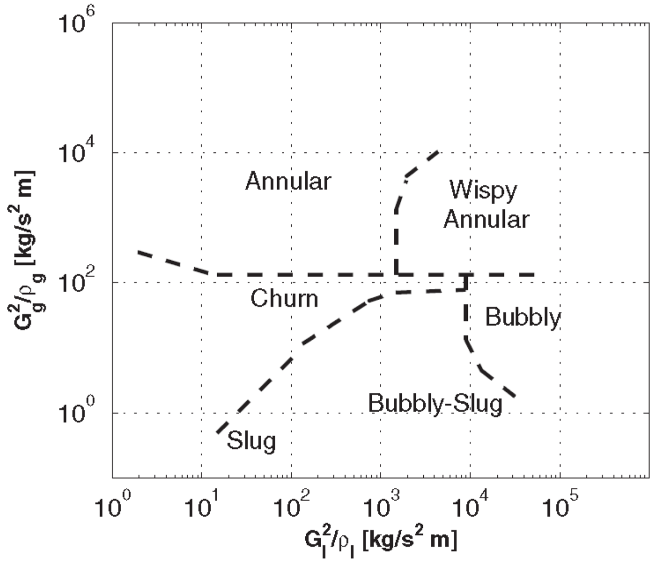
Forced Convection Boiling: Internal Flow



Heat transfer coefficient almost independent of the heat flux but depends on the velocity and quality factor

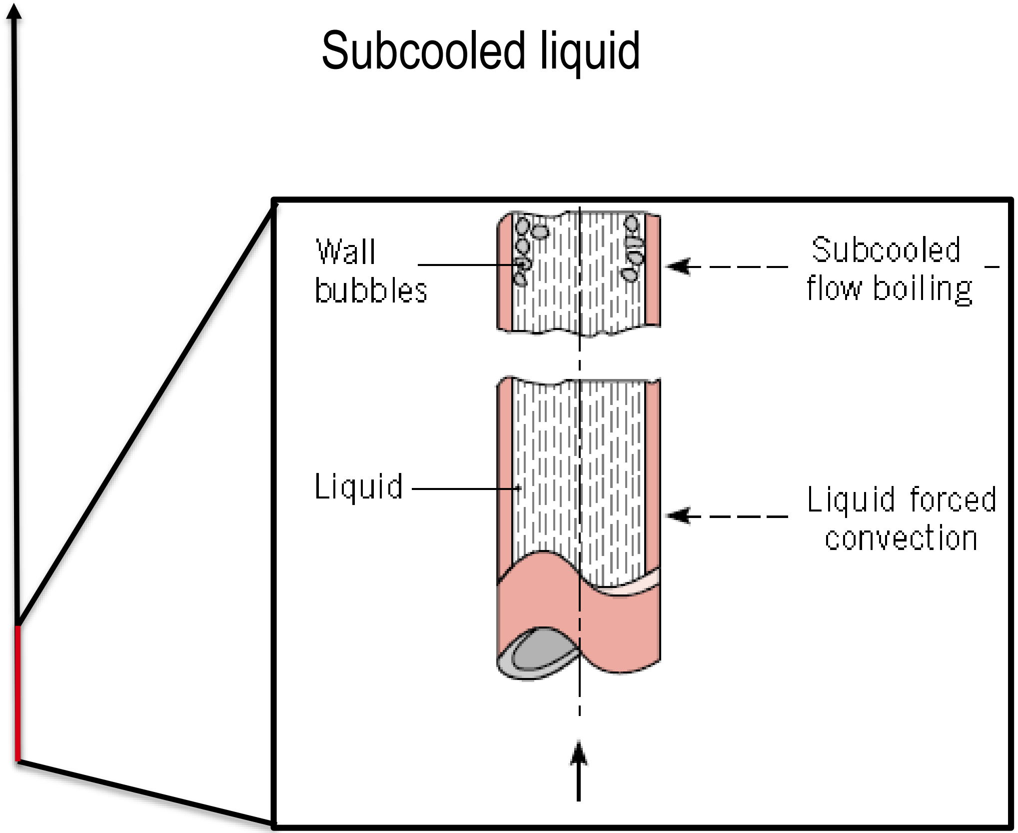
Vapor quality: $X = \dot{m_v}/\dot{m_{tot}}$

G = $\dot{m_{tot}}$ $\quad G_l = (1-x)G; \quad G_g = xG$



Forced Convection Boiling: Internal Flow

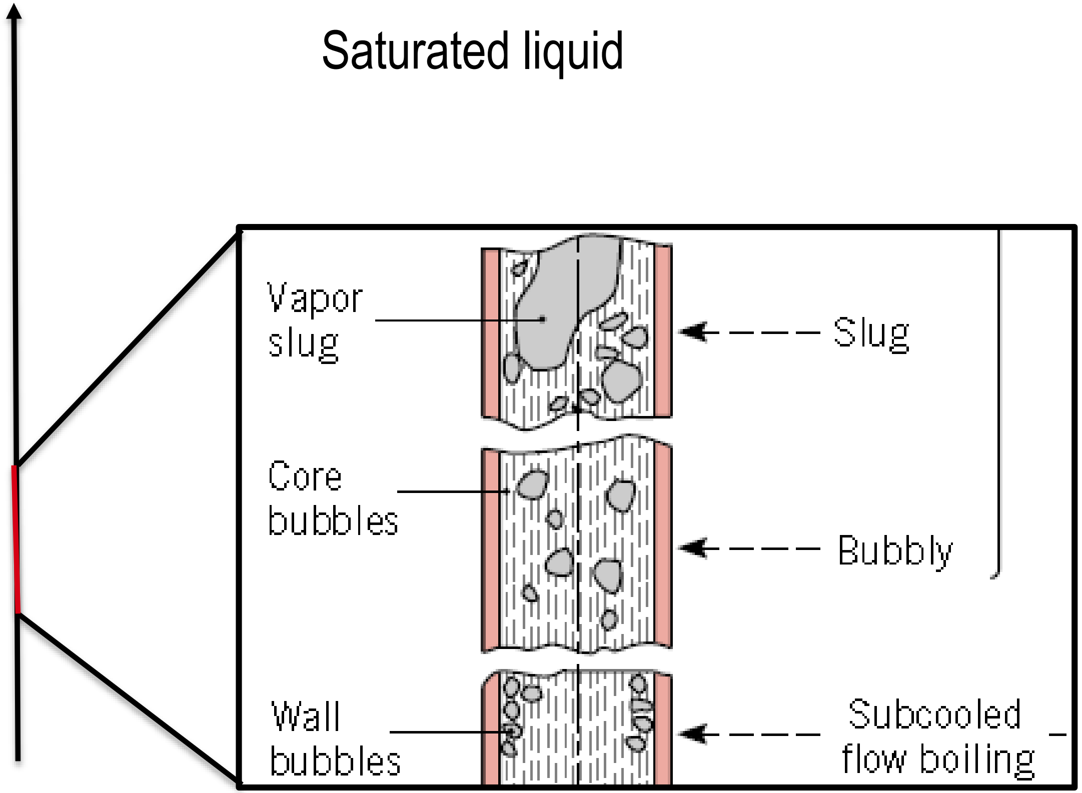
Subcooled liquid



Strong radial T gradients: bubbles nucleate at the wall and saturated liquid flows in the core

Single-phase internal-flow convection correlation

Forced Convection Boiling: Internal Flow



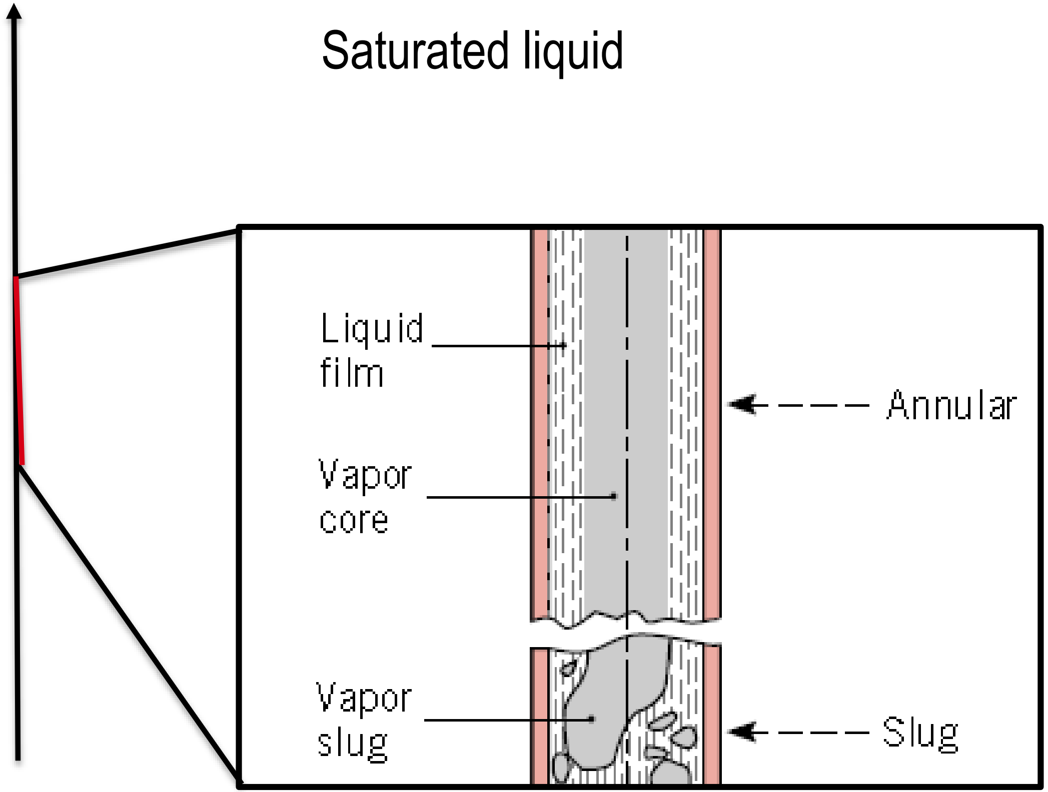
The core of the liquid reaches saturation temperature and bubbles can be present at any radial position within the tube:
→ time-averaged mass-fraction of vapor X > 0 at any r

Mean vapor mass fraction:

$$\overline{X} \equiv \frac{\int_{A_c} \rho u(r,x) X dA_c}{\dot{m}}$$

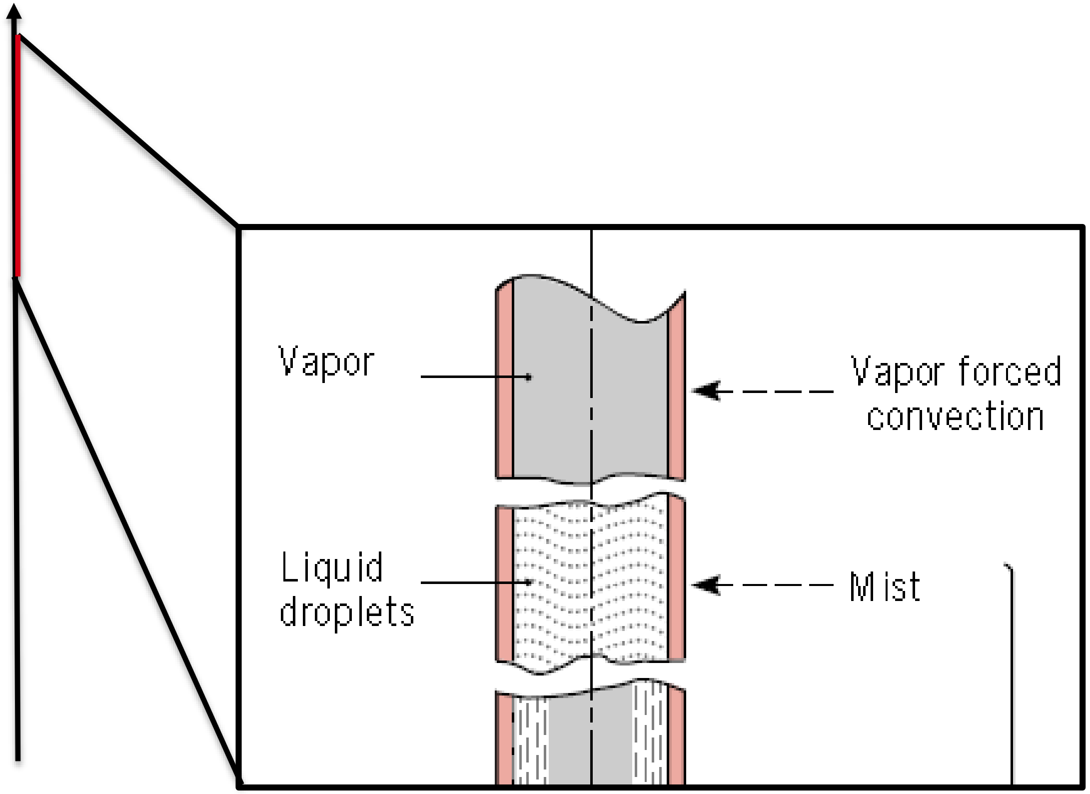
→ mean fluid velocity u_m increases with x

Forced Convection Boiling: Internal Flow



In the annular flow the liquid moves along the walls while the vapor moves at much higher velocity within the core.

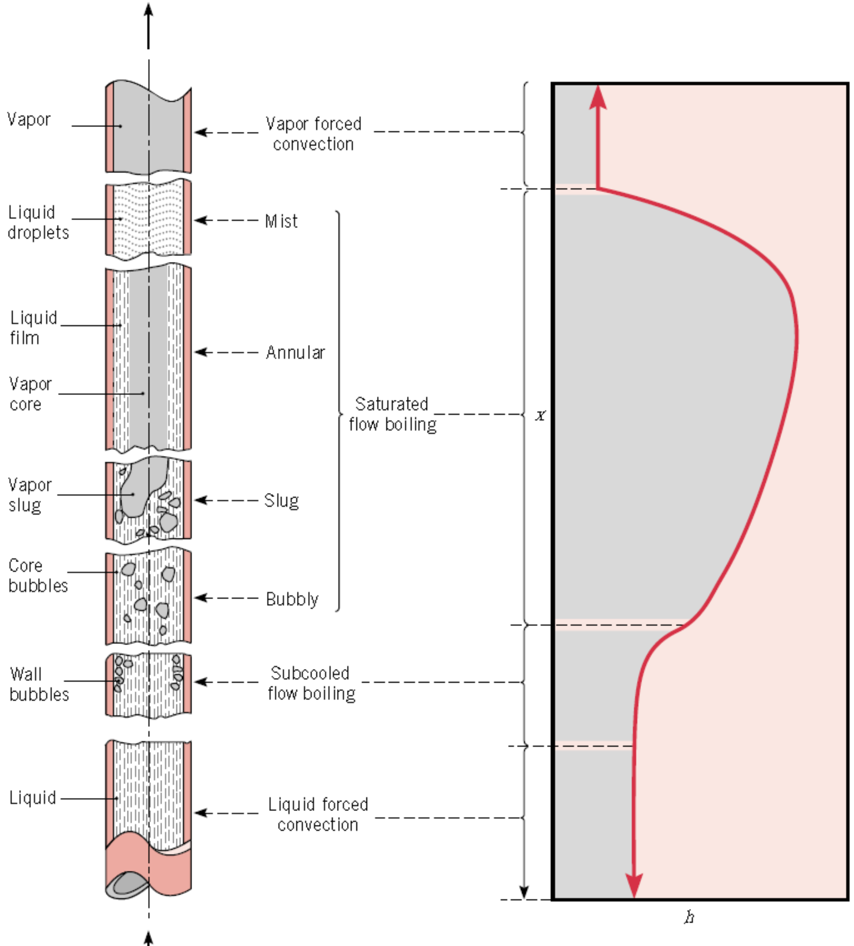
Forced Convection Boiling: Internal Flow



At the end the vapor is superheated, there are no droplets and a single-phase forced-convection with vapor is established

After a transition zone where the annular films breaks up, eventually the entire surface of the tube is dry.

Forced Convection Boiling: Internal Flow



Single-phase h (vapor)

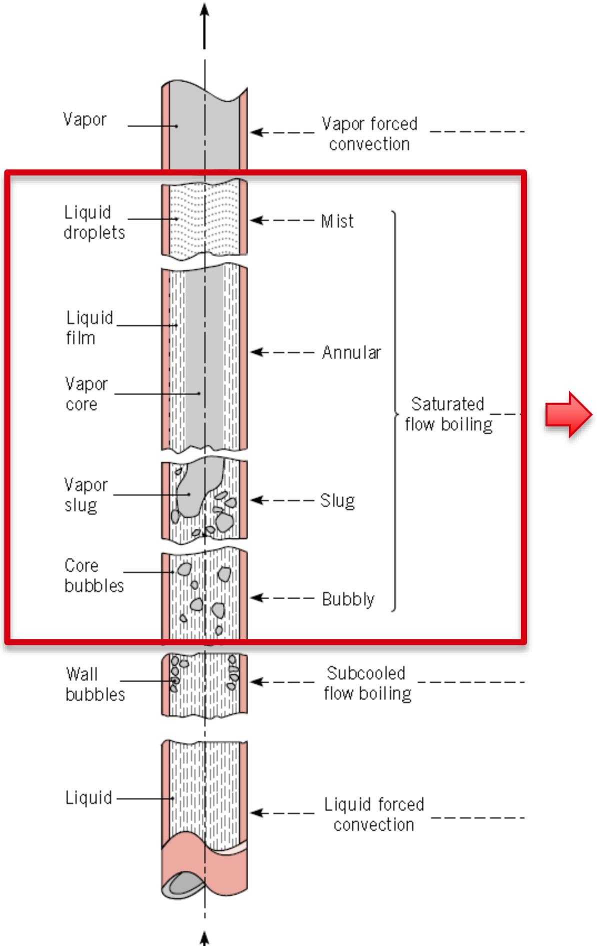
Very rapid decrease

Continuous increase

Very rapid increase

Single-phase h (liquid)

Forced Convection Boiling: Internal Flow



Saturated flow boiling in smooth circular tubes

Forced Convection Boiling: Internal Flow

Saturated flow boiling in smooth circular tubes: use the largest h between

$$\frac{h}{h_{sp}} = 0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1} \bar{X}^{0.16}(1-\bar{X})^{0.64} f(Fr) + 1058\left(\frac{q_s''}{\dot{m}'' h_{fg}}\right)^{0.7} (1-\bar{X})^{0.8} G_{s,f}$$

$$\frac{h}{h_{sp}} = 1.136\left(\frac{\rho_l}{\rho_v}\right)^{0.45} \bar{X}^{0.72}(1-\bar{X})^{0.08} f(Fr) + 667.2\left(\frac{q_s''}{\dot{m}'' h_{fg}}\right)^{0.7} (1-\bar{X})^{0.8} G_{s,f}$$

TABLE 10.2 Values of $G_{s,f}$ for various surface–liquid combinations [27, 28].

Fluid in Commercial Copper Tubing	$G_{s,f}$
Kerosene	0.488
Refrigerant R-134a	1.63
Refrigerant R-152a	1.10
Water	1.00
For stainless steel tubing, use $G_{s,f} = 1$.	

	Vertical tubes	Horizontal tubes Fr>0.04	Horizontal tubes Fr<0.04
$f(Fr)$	1	1	$f(Fr) = 2.63Fr^{0.3}$

Where $\bar{X}(x) = vapor\ quality = q_s''\pi D x/(\dot{m}\ \ h_{fg})$

$\dot{m}'' = \dot{m}/A_c$

h_{sp} = single-phase convection coefficient calculated with the right correlation for internal forced convection assuming all the mass is flowing in the liquid form. Use the saturation temperature as reference.

$$Fr = \frac{(\dot{m}''/\rho_l)^2}{gD}$$

Forced Convection Boiling: Internal Flow (Example)

0.6 kg/s of saturated H_2O at $T_b = 207°C$ flows in a 5 cm diameter vertical tube heated at a rate of 184,000 W/m^2. Find the wall temperature at a point where the quality x is 20%.

TABLE A.6 *Continued*

Temperature, T (K)	Pressure, p (bars)^b	Specific Volume (m^3/kg) $v_f \cdot 10^3$	v_g	Heat of Vaporization, h_{fg} (kJ/kg)	Specific Heat (kJ/kg · K) $c_{p,f}$	$c_{p,g}$	Viscosity ($N \cdot s/m^2$) $\mu_f \cdot 10^6$	$\mu_g \cdot 10^6$	Thermal Conductivity (W/m · K) $k_f \cdot 10^3$	$k_g \cdot 10^3$	Prandtl Number Pr_f	Pr_g	Surface Tension, $\sigma_f \cdot 10^3$ (N/m)
440	7.333	1.110	0.261	2059	4.36	2.46	162	14.50	682	31.7	1.04	1.12	45.1
450	9.319	1.123	0.208	2024	4.40	2.56	152	14.85	678	33.1	0.99	1.14	42.9
460	11.71	1.137	0.167	1989	4.44	2.68	143	15.19	673	34.6	0.95	1.17	40.7
470	14.55	1.152	0.136	1951	4.48	2.79	136	15.54	667	36.3	0.92	1.20	38.5
480	17.90	1.167	0.111	1912	4.53	2.94	129	15.88	660	38.1	0.89	1.23	36.2

Forced Convection Boiling: Internal Flow (Example)

0.6 kg/s of saturated H_2O at $T_b = 207°C$ flows in a 5 cm diameter vertical tube heated at a rate of 184,000 W/m^2. Find the wall temperature at a point where the quality x is 20%.

$$\dot{m}'' = \dot{m}/A_c = \frac{0.6}{0.001964} = 305.6 kg/m^2 s$$

$$Re = \frac{\dot{m}'' D}{\mu} = 1.18 \cdot 10^5 > 2300 \text{ (turbulent)}$$

$$Nu_D = 0.023 Re_D^{4/5} Pr^{0.4} = 251$$

$$h_{sp} = \frac{Nu_D k}{D} = 3318\, W/m^2 K$$

$$\frac{h}{h_{sp}} = 0.6683 \left(\frac{\rho_l}{\rho_v}\right)^{0.1} \bar{X}^{0.16} (1-\bar{X})^{0.64} + 1058 \left(\frac{q_s''}{\dot{m}'' h_{fg}}\right)^{0.7} (1-\bar{X})^{0.8} = 3.8$$

$$\frac{h}{h_{sp}} = 1.136 \left(\frac{\rho_l}{\rho_v}\right)^{0.45} \bar{X}^{0.72} (1-\bar{X})^{0.08} + 667.2 \left(\frac{q_s''}{\dot{m}'' h_{fg}}\right)^{0.7} (1-\bar{X})^{0.8} = 4.7$$

$\Rightarrow$ $h = 15496.7\, W/m^2 K$

$q_s'' = h(T_s - T_{sat})$ $\Rightarrow$ $T_s = 207 + \frac{184000}{15496.7} = 218C$

$\Delta T_e = 11C$

	Vertical tubes
$f(Fr)$	1

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Learning Objectives:

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Jupyter Notebook

https://go.epfl.ch/ConvectionNotebook

Run -> Run All Cells

3. Internal forced convection

Next Week

- ❑ Condensation
  - ❑ Laminar Film Condensation on a Vertical Plate
  - ❑ Film Condensation on a Vertical Plate: Correlations
  - ❑ Film Condensation on Radial Systems
    - ❑ Correlations for Laminar Flow
    - ❑ Overall Heat Transfer Coefficient

Learning Objectives:

- ❑ Understand condensation
- ❑ Calculate convection coefficient in selected cases